NUMERICAL AND EXPERIMENTAL ANALYSIS OF THE TRANSFER LENGTH AND ITS INFLUENCE ON THE ANCHORAGE ZONE DESIGN OF PRETENSIONED CONCRETE MEMBERS.

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ABSTRACT:

In order to optimize the end block of a prestressed girder, nonlinear finite element models are frequently used. This way the stresses and possible cracks in the anchorage zones can be predicted in a more reliable manner. However, a preliminary parametric study of nonlinear finite element models has shown that the transfer length has a major influence on the stresses in the concrete and in the reinforcement, and on the crack formation. In this paper this transfer length is examined, firstly by performing a parametric study of the formulations found in literature, secondly by measurements on beams produced at a precast concrete plant. The aim of this parametric study and the experimental research is to get further insight into the transfer length function as required for further numerical analysis of the end zones.

Keywords: End Zones, FEM, Pretensioned Girders, Transfer length

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INTRODUCTION

Pretensioned concrete girders have been used for many years in construction. Nevertheless, optimization is still possible, especially regarding the anchorage zones. These are typically subjected to different types of stresses due to the local transfer of the prestressing force. Generally, the beams are provided with an end block, and are designed by making use of analytical or strut-and-tie models. However, these models lack clarity regarding the reinforcement design, the transfer length, the width of possible cracks, etc. Moreover, the calculated reinforcement does not automatically imply the most economic solution. Furthermore, the need for the end block itself is not obvious. By using a nonlinear finite element model, the stresses in the anchorage zone due to the prestressing forces can be predicted in a more reliable way. Analyzing these models shows that the transfer length is the most important parameter. Several transfer length measurements were performed on the production line of a precast beam manufacturer during the prestressing operation. The experimental results are compared with data from literature.

FINITE ELEMENT MODELING

Nonlinear finite element modeling allows simulating a girder in an accurate way, and the behavior of the end zone can be analyzed directly in 3D with the correct material laws. In order to illustrate the need for an accurate assessment of the transfer length, the results of a nonlinear analysis on a typical prismatic girder without enlarged end zone are shown. The finite element model is based on the contributions of Okumus and Oliva [1,2], and consists of an I-shaped cross-section with a height of 600 mm, a width of 300 mm and 9 seven wire strands of 93 mm² in cross-section (Figure 1).

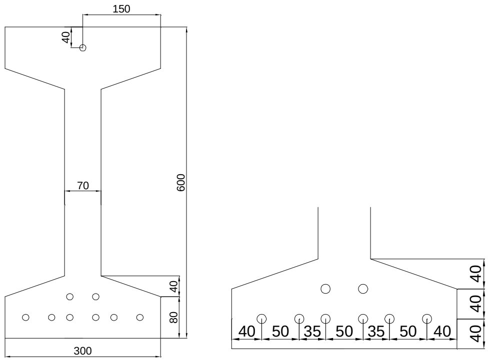


Figure. 1 Front view and detail of the modeled geometry

A reduced length of 4 meter is chosen in order to minimize the calculation time while the remainder of the beam is represented by adequate boundary conditions (Figure 2).

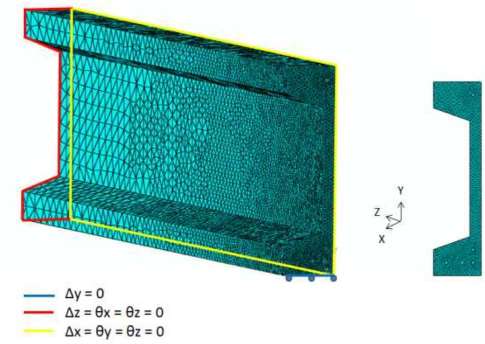


Figure. 2 Boundary conditions

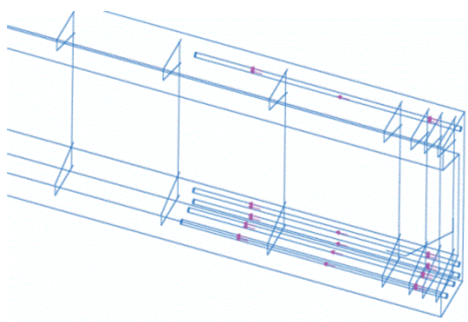


Figure. 3 Modeled reinforcement

The passive reinforcement bars are modeled as linear elastic embedded elements, as they are not expected to yield during the prestress transfer. On the other hand, the strands are modeled as circular holes over the transfer length (Figure 3) [3]. A linearly distributed shear stress is assigned along the outline of the holes. This shear stress has its maximum at the end face and decreases to zero at the end of the transfer length [4].
Regarding the embedded steel, only the density, the modulus of elasticity, and the Poisson's ratio need to be defined. The values of these parameters are given in Table 1.

Density ρ [kg/m³]	7800
Modulus of elasticity E_s [MPa]	200000
Poisson ratio ν_s [-]	0.3

Table 1 Material properties of steel

The material parameters of the concrete are based on the concrete damaged plasticity model as provided in the Abaqus material library. This model is appropriate for simulating the nonlinear behavior of concrete in compression as well as in tension. The basic values of the concrete model are given in Table 2.

Density ρ [kg/m³]	2500
Poisson ν_s [-]	0.2
Dilatation angle [°]	36
Excentricity [mm]	0.1
f_{b0}/f_{c0} [-]	1.16
K [-]	0.666

Table 2 Material properties of concrete

The nonlinear parameters for the compressed case are determined by using the fib Model Code (2010) [5], in combination with the AASHTO LRFD Bridge Design Specifications [3] for the linear part of the stress-strain diagram. The modulus of elasticity is calculated by using the ASHTOO [3] instead of the Model Code [5]. In the tensile part, the linear part uses the modulus of elasticity mentioned above, whereas the relationship between the concrete tensile stress and the crack opening for concrete in tension is based on the fib Model Code [5] (Figure 4).

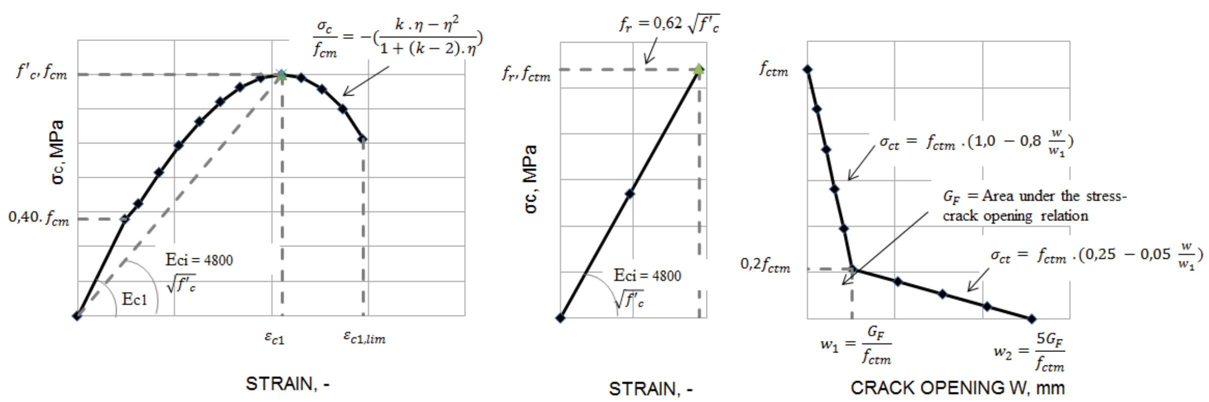
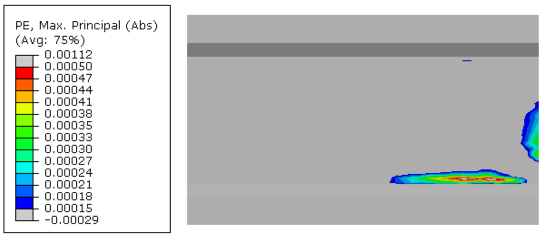


Figure. 4 Constitutive model for concrete in compression (left) and tension (right) [1, 2, 6]

Figure 5 shows a typical result of the principal tensile strains representative for cracked concrete zones in view of the model as represented by Figure 4. Figure 6 displays the corresponding rebar stresses in the stirrups and the oblique rebar.



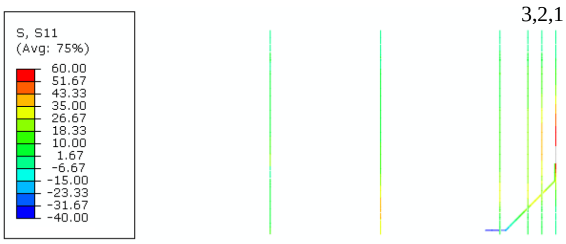


Figure. 5 Maximum principal strains in the concrete   Figure. 6 Stresses in the reinforcement

During the analysis different parameters were studied such as the transfer length, the concrete strength, the influence of varying fracture energy, etc. The preliminary conclusion is that the transfer length, which is examined by varying its value from 40 to 80 times the nominal strand diameter, has a major influence on the stresses in the reinforcement. It can be noticed that the rebar stresses increase remarkably when the transfer length is lower than 60 times the strand diameter. For the model presented, the stresses in the stirrups and the oblique rebar show a nonlinear descending trend when increasing the transfer length (Figure. 7).

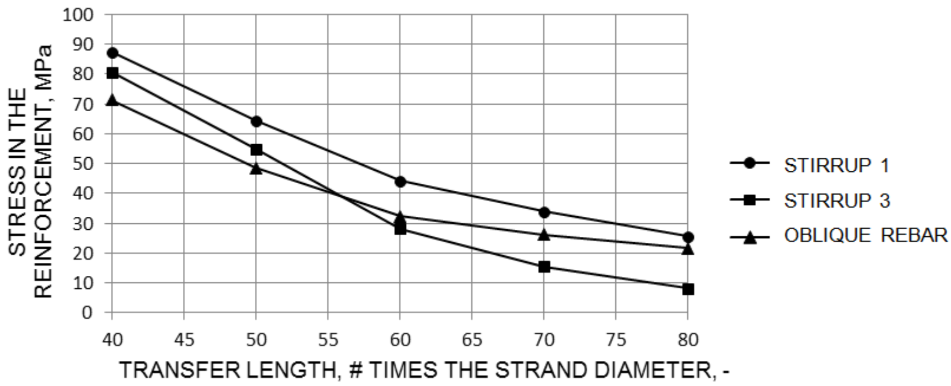


Figure. 7 Transfer length as a function of the stress in the reinforcement

For that reason it is useful to examine the different formulas from literature, in order to gain insight into the different influencing parameters of the transfer length. Moreover the results will be compared with measurements on beams produced at the precast concrete plant.

PARAMETRIC STUDY OF THE FORMULAS FOR TRANSFER LENGTH ESTIMATIONS FROM LITERATURE

Over the years, the transfer length in a prestressed girder has been examined extensively. In view of the relevance of this transfer length in the end zone reinforcement assessment through nonlinear finite element modeling, a parametric study of formulas from literature is conducted as a matter of comparison with the measured values given further in this paper. The parametric study is based on the work of Pozolo [7] and J.R. Marti-Vargas et al. [8] and compares 16 formulations from 13 sources (See Table 3).

ACI 318-11 [6]	$L_T = \frac{\sigma_{pcs}\emptyset}{20,7}$	Balázs [18]	$L_T = \frac{3,15}{\emptyset}\sqrt[5]{\sigma_{pcs}^3/f_{ci}^2}$
Martin and Scott [10]	$L_T = 80\emptyset$	AASHTO [3]	$L_T = 60\emptyset$
Zia and Mostafa [15]	$L_T = a\frac{\sigma_{pi}\emptyset}{f_{ci}} - b$	Lane [12]	$L_T = \frac{4\sigma_{pt}\emptyset}{f_c} - 127$
Mitchell et al. [16]	$L_T = \frac{\sigma_{pi}\emptyset}{20,7}\sqrt{\frac{20,7}{f_{ci}}}$	Kose and Burkett [13]	$L_T = 0,05\frac{\sigma_{pt}(1-\emptyset)^2}{\sqrt{f_c}}$

Shahawy et al. [11]	$L_T = \frac{\sigma_{pi}\emptyset}{20{,}7}$	Mahmoud et al. [19]	$L_T = \frac{\sigma_{pi}\emptyset}{\alpha_t f_{ci}^{0{,}67}}$
Cousins et al. [17]	$L_T = \frac{\sigma_{pcs}A_p}{\pi\emptyset U'_t\sqrt{f_{ci}}} + 0{,}5\frac{U'_t\sqrt{f_{ci}}}{B}$	MC 2010 [14]	$L_T = \alpha_{p1}\alpha_{p2}\alpha_{p3}\frac{A_p}{\pi\emptyset}\frac{\sigma_{pi}}{\eta_{p1}\eta_{p2}f_{ctdi}}$
EC2 - 2004 [9]	$L_T = \alpha_1\alpha_2\emptyset\frac{\sigma_{pi}}{\eta_{p1}\eta_{p2}f_{ctdi}}$		

Table 3 Formulas parametric study

Given the wide range of parameters present in the various formulations, the parametric study was conducted for (seven wire) strands with diameters of 9.3 mm and 12.5 mm, with a gradual and sudden release after 1, 3, and 5 days, and for concrete strengths C55/67 and C60/75. This selection is based on the materials used by the manufacturer and on the beams' manufacturing process. This way the experimental results can be compared with the theoretical estimations based on literature. Table 4 gives the values of the fixed parameters, according to the work of Marti-Vargas et al [8] : $\sigma_{pt} = 0.75f_{pu}$, $\sigma_{pi} = 0.93\sigma_{pt}$, $\sigma_{pcs} = 0.8\sigma_{pt}$ and $\sigma_{pa} = 0.9f_{pu}$. Table 5 shows the variable parameters.

f_{pu}	tensile strength of prestressing strands	1860	MPa
σ_{pt}	initial prestress in prestressing strand prior to release	1395	MPa
σ_{pcs}	effective stress in prestressing strand after all prestress	1116	MPa
σ_{pi}	effective stress in prestressing strand just after prestress transfer	1297	MPa
σ_{pa}	maximum stress in strand at loading	1674	MPa
s	Coefficient which depends on the cement type	0.18	[-]

Table 4 Fixed parameters

f_{ci}	concrete compressive strength at time of release [eq. 3.1 of EC2 with s=0,18 for CEM I 52,5 R]	[MPa]
f_{cl}	concrete compressive strength at loading [fcl = 1.5fci]	[MPa]
f_{ck}	concrete compressive strength at 28 days	[MPa]
f_{ct}	concrete tensile strength at 28 days	[MPa]
$f_{ctd(i)}$	concrete tensile strength at time of release	[MPa]
Ø	nominal diameter of prestressing strand	[mm]
A_p	cross-sectional area of prestressing reinforcement	[mm²]
t	time of release	[days]
β_{cc}	coefficient which depends on the age of the concrete	[-]
P_k	choice of prestress force	[kN]

Table 5 Variable parameters

The choice of parameters given above leads to 12 combinations, for which the calculated transfer lengths are listed in table 6.
For the results at a release time of one day it should be noted that although formulation 3.1 from EC2 [9] for calculating the compressive strength at early age is only valid for ages between 3 and 28 days, the formulation is also used for a concrete age of one day.

From Table 6 it is easily observed that the transfer length foremost depends on the strand diameter with larger transfer lengths corresponding to larger strand diameters. Since the effective stress in the prestressing strands is kept constant for the 4 formulations (ACI [6], Martin and Scott [10], Shahawy et al. [11], AASHTO [3]), the strand diameter is the only parameter. However, as the coefficients in these formulations are not equal they render transfer length predictions differing up to 54% compared to the smallest value. The formulations of Lane [12] and Kose and Burkett [13] consider concrete strength as well. MC

2010 [14], EC2 [9] and Zia and Mostafa [15] also make a distinction in the way of release. Regarding this time dependent effect, and looking at the calculated values of Zia and Mostafa [15], the transfer lengths for sudden release are in 11 of the 12 cases larger than for gradual release, with a maximum difference of 9.5%. The values of MC 2010 [14] and EC2 [9], on the other hand, indicate a 20% larger transfer length in case of sudden release, which is related to the parameter α_1. If the time of release is further evaluated, the transfer length decreases with increasing age of the concrete. This is noticeable in every formula except for the 4 equations which depend on the strand diameter, and in the equations by Lane [12] and Kose and Burkett [13]. Finally, when the strand diameter and time of release are kept constant, it can be determined that the transfer length reduces as the concrete strength decreases. In case of a strand diameter of 9.3mm, the largest values exceed the lowest ones by 13%, while for the 12.5mm strand diameter this maximum difference is 12%.

parametric study transfer length	Ø9.3/C55-67/1d	Ø9.3/C55-67/3d	Ø9.3/C55-67/5d	Ø9.3/C60-75/1d	Ø9.3/C60-75/3d	Ø9.3/C60-75/5d	Ø12.5/C55-67/1d	Ø12.5/C55-67/3d	Ø12.5/C55-67/5d	Ø12.5/C60-75/1d	Ø12.5/C60-75/3d	Ø12.5/C60-75/5d
ACI 318-11 [6]	501	501	501	501	501	501	674	674	674	674	674	674
Martin and Scott [10]	744	744	744	744	744	744	1000	1000	1000	1000	1000	1000
Zia and Mostafa (gradual) [15]	741	417	351	663	375	315	1016	580	491	910	524	444
Zia and Mostafa (sudden) [15]	805	431	355	714	382	314	1123	619	517	1000	554	462
Cousins et al. [17]	793	620	578	755	594	554	1051	818	762	999	783	730
Shahawy et al. [11]	583	583	583	583	583	583	783	783	783	783	783	783
Balázs [18]	583	473	446	559	456	430	784	636	599	752	613	578
Mitchell et al. [16]	577	445	413	548	425	395	776	598	555	737	571	530
Lane [12]	817	817	817	738	738	738	1141	1141	1141	1036	1036	1036
Mahmoud et al. [19]	652	460	416	608	432	391	876	618	559	817	581	526
Kose and Burkett [13]	648	648	648	620	620	620	1244	1244	1244	1191	1191	1191
EC2 - 2004 (gradual) [9]	851	569	514	812	543	480	1144	765	690	1092	730	645
EC2 - 2004 (sudden) [9]	1064	711	642	1015	679	600	1430	956	863	1365	912	806
MC 2010 (gradual) [14]	797	533	481	761	509	449	1061	709	640	1012	677	598
MC 2010 (sudden) [14]	996	666	601	951	636	562	1326	886	800	1266	846	748
AASHTO [3]	558	558	558	558	558	558	750	750	750	750	750	750
	1	2	3	4	5	6	7	8	9	10	11	12
Average	732	573	540	696	548	515	1011	799	754	961	764	719
Standard deviation	159	120	133	145	117	130	222	199	218	202	192	212
Minimum	501	417	351	501	375	314	674	580	491	674	524	444
Maximum	1064	817	817	1015	744	744	1430	1244	1244	1365	1191	1191
# times strand diameter	79	62	58	75	59	55	81	64	60	77	61	58

Table 6 Calculated transfer length [mm] based on various sources

Figure 8 shows the minimum, maximum, and average transfer length values for the 12 considered scenarios. Clearly there is a big scatter in the results. Given this observation, transfer length measurements were carried out during normal production at the prefab concrete plant.

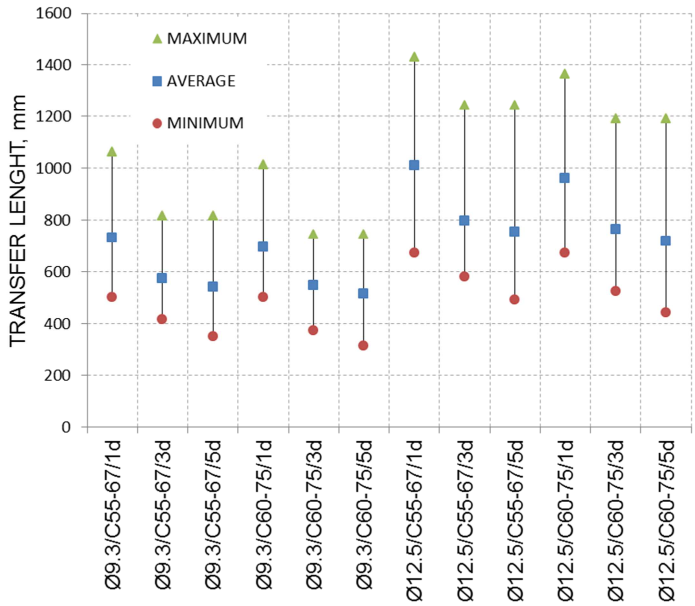


Figure. 8 Summary parametric study

EXPERIMENTAL WORK

As mentioned in the first part, measurements were conducted on beams produced at the plant during normal production. A non-shrink adhesive was used to attach several measuring points to the concrete's surface at the level of the lower strands. With an invar reference bar, provided with two conical locating points, the measurement points were placed at a fixed distance of 100 mm. Near the end face of the beam the measuring points were placed in overlay, with an intermediate distance of 50 mm in order to obtain more accurate results near the beam end. The distance between the points is measured with a DEMEC mechanical strain gauge, with a resolution of 16 microstrain. The measurements render strain values based on a 100 mm gauge at 50 or 100 mm intervals which are presented hereafter.

Figure. 9 Measurement locations

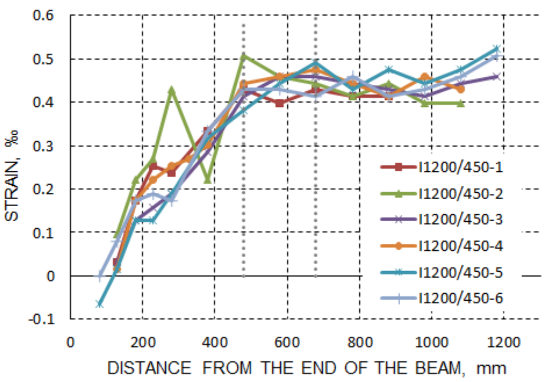
35 beams, with 4 different geometries and 2 types of concrete, were instrumented and measured over 7 production lines. All the strands were released gradually, except for beams 3 to 6. Equally not every beam was prestressed with the same prestress force (See Table 7).
Although all beams of equal geometry were cast on a single production line, the concrete was made at different days, so the concrete had a different strength at time of release. These exact strength values, however, were not available for most beams. Therefore, the compressive strength was determined on cubes (f_{ccubm}) of 150 mm at 28 days (see Table 7).

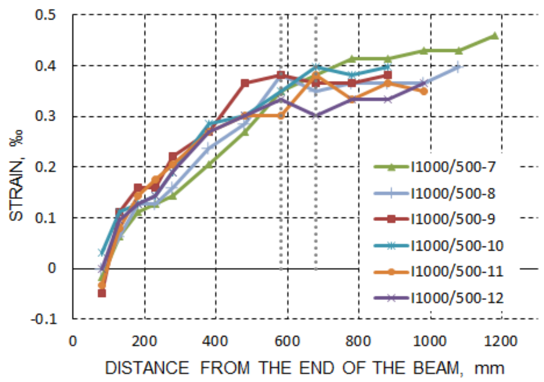
beam	concrete strength class	age concrete [days]	compressive strenght at 28 days [MPa]	prestress force strands lower flange [kN]	prestress force debonded strands lower flange [kN]
I1200/450-1	C60/75	20	80.9	3875.2	553.6
I1200/450-2		2	78.7		
I1200/450-3	C60/75	1	94.4		
I1200/450-4		1	94.4		
I1200/450-5		2	-		
I1200/450-6		2	-		
I1000/500-7	C55/67 SCC	1	-	2768	553.6
I1000/500-8		2	69.9		
I1000/500-9		3	73.9		
I1000/500-10		6	71.6		
I1000/500-11		8	73.4		
I1000/500-12		7	76		
I1400/600-13	C55/67 SCC	3	73.9		
I1400/600-14		7	76		
I1400/600-15		6	71.6		
I1400/600-16		8	73.4		

beam	concrete strength class	age concrete [days]	compressive strenght at 28 days [MPa]	prestress force strands lower flange [kN]	prestress force debonded strands lower flange [kN]
I1600/600-17	C55/67 SCC	7	80.3	5259.2	830.4
I1600/600-18		2	77.5		
I1600/600-19		8	75.4		
I1600/600-20		5	76.4		
I1600/600-21		9	76		
I1600/600-22		6	76.3		
I1600/600-23		?	70.4		
I1450/600-24	C60/75	2	90.9	4860.8	1107.2
I1450/600-25		7	91.5		
I1450/600-26		3	92.9		
I1450/600-27		8	92		
I1450/600-28		4	92.1		
I1450/600-29		9	82.1		
I1450/600-30	C60/75	4	97.7		
I1450/600-31		7	93.3		
I1450/600-32		5	89.7		
I1450/600-33		10	87.5		
I1450/600-34		6	92.1		
I1450/600-35		11	83.8		

Table 7 Overview tested beams

From Table 7, it can be concluded that the average value of the cubic compressive strengths (f_{ccubm}) at 28 days of concrete class C55/67 is 74.5 MPa. According to EN 206:2014, section 8.2.1.3, this value has to be larger than f_{ccubk} + 4 MPa (71.0 MPa). For this concrete type the specimens' strength meets the requirement of the specified concrete strength class. For the concrete strength class C60/75 these values are 89.3 MPa and 79.0 MPa respectively, so the measured strength exceeds the required strength with 10 MPa. In Figure 10 the measured strain values are shown separately and in Figure 11 all measurements are combined in one graph. Based on the obtained curves it is difficult to determine the actual transfer length. Vertical dotted lines on the graphs in Figure 10 indicate the approximate end of the transfer length, based on the gradient of the curve. In the first graph, two vertical lines can be marked, one at a distance of 480mm from the beam's end, and one at a position of 680mm. These lines indicate the minimum and maximum distance from which the strains remain at a constant level. In the second graph, considering beam 7 up to 12, the transition point is located between 580mm and 680mm. For beams 1 to 12 and 17 to 23 a similar curve shape is noticed, as well. The curves of beam 24 to 35, on the other hand, show an increasing trend until approximately 280mm, then the slope changes and a more slowly ascending trend is observed. The strain values for beam 13 to 16 even keep increasing.





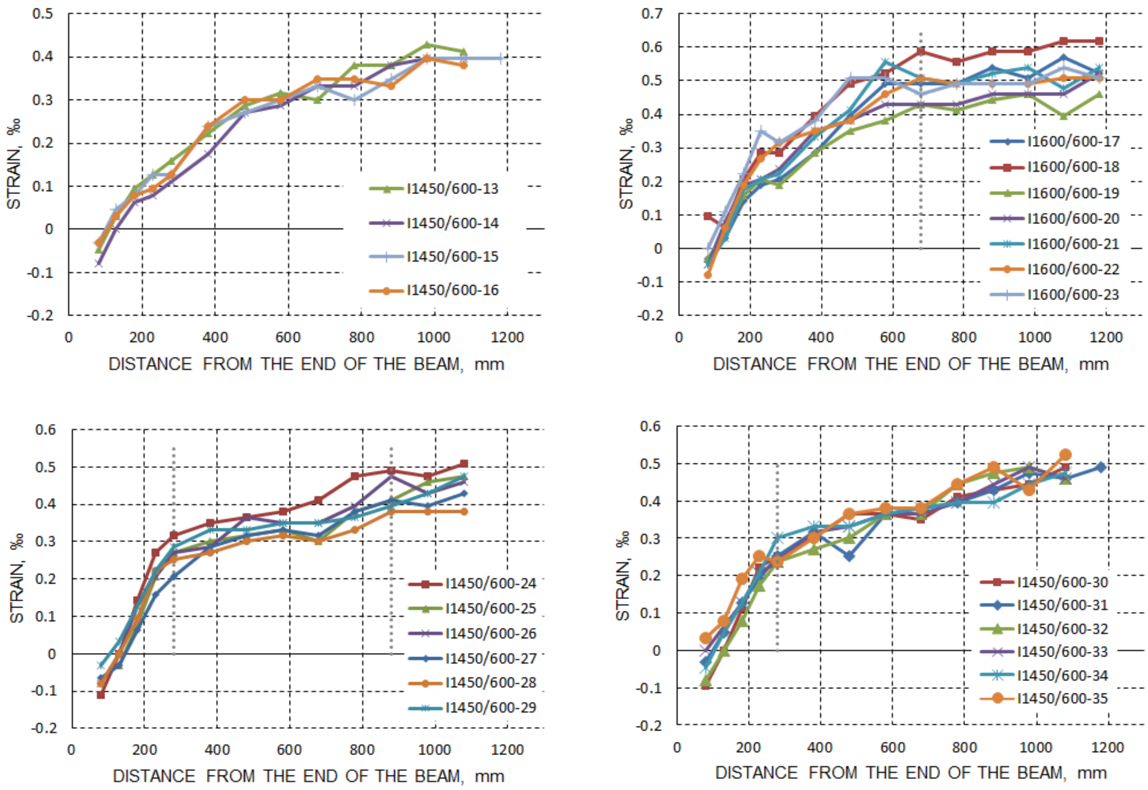


Figure. 10 Results of the strain measurements in function of the distance from the end of the beam

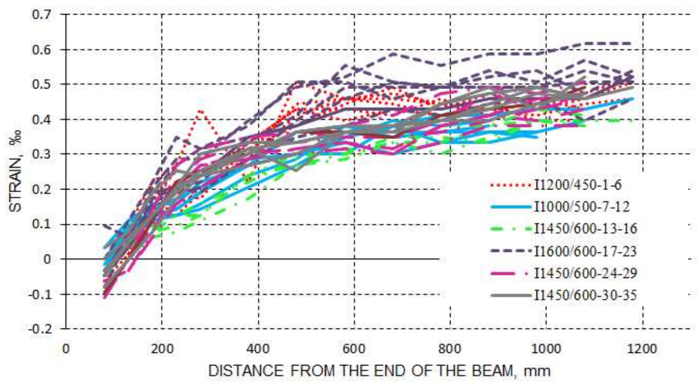


Figure. 11 Overview of all the strain measurements in function of the distance from the end of the beam

Location of the measuring points

Regarding the different graphs of the end zone strain measurements (Figure 10), three different shapes of curves can be observed, as mentioned before. This can be explained by the position of the measuring points relative to the centroid of the strands. In order to clarify, the three strand configurations of the beams of equal width, are presented in Figure 12. Considering the group of lower strands, it can be determined that the measurement points of beams 24 to 35 are situated approximately at the level of the centroid of the active strands. Beams 17 to 23 have 3 rows of 12 strands of which 4 debonded strands, and 1 row of 2 strands. The measuring points were attached between the first and the second layer, at 80 mm from the bottom of the beam, and not at the centroid of the active strands, at 110 mm (Figure 12). This is thought to influence the strain measurements, resulting in the different shapes of the curves (Figure 10). Looking at beams 13 to 16, the bottom layer consists of 10 strands, the second one of 8 strands and the top layer of only 2. For these beams the measurement dots were placed at the bottom layer level and not at the centroid of all strands, as the outer strands of this bottom layer are closer to the lateral edges of the lower flange. In general, the evolution of the measured strain in the transfer zone depends on the position of the measuring points. Moreover, for beams 13 to 16, the smaller number of strands and the fact that the strands are located in the central part of the flange cause a lateral dispersion over a longer distance resulting in a slower strain increase. In future measurements, the measuring points will be attached at different distances from the lower fiber to confirm this observation.

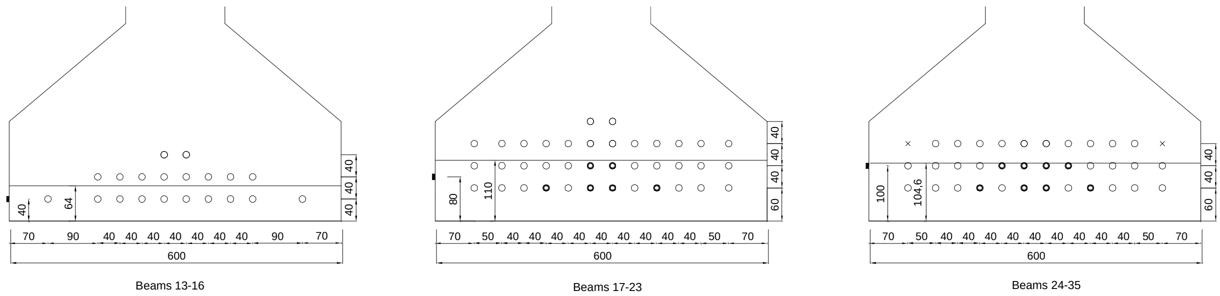


Figure. 12 Strand configuration and location of measuring points

Validation of the parametric study

A parametric study of the transfer length estimation formulas was carried out. The parameters studied showed that the concrete strength class, the time of release, the strand diameter, and the way of prestressing are determining factors for the transfer length. These parameters will be investigated based on the experimental results.

- *Concrete strength*

Two concrete strength classes were used: C60/75 for beams 1 to 6 and C55/67 for beams 7 to 12. Despite these different strengths for beam series with altered geometries and varying prestress forces, the transfer length measurements of the two series can be compared. Analyzing the results of beams 1 to 6 and 7 to 12 (Figure 10) it appears that the graph shape of the first beam series approaches the horizontal asymptote faster. This confirms that a higher concrete strength results in a shorter transfer length.

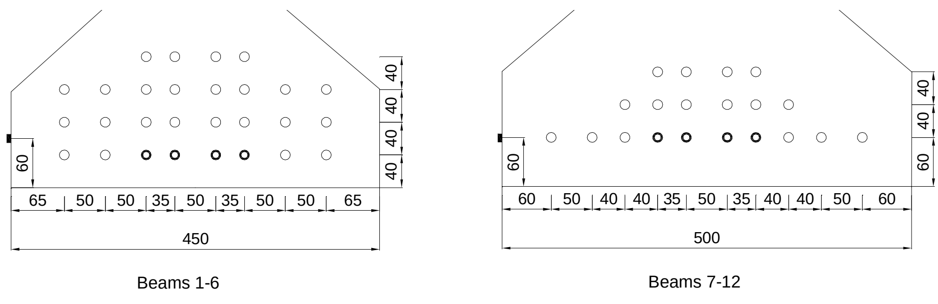


Figure. 13 Position strands beams 1 to 12

- *The time of release*

Only for beams 24 to 29 and 30 to 35, the concrete strength is known at the time of strand release. Figure 14 shows these measured compressive strengths f_{ccubm} at the time of release as well as the early age compressive strength evolution based on the average measured compressive strengths f_{ccubm} at 28 days [3].

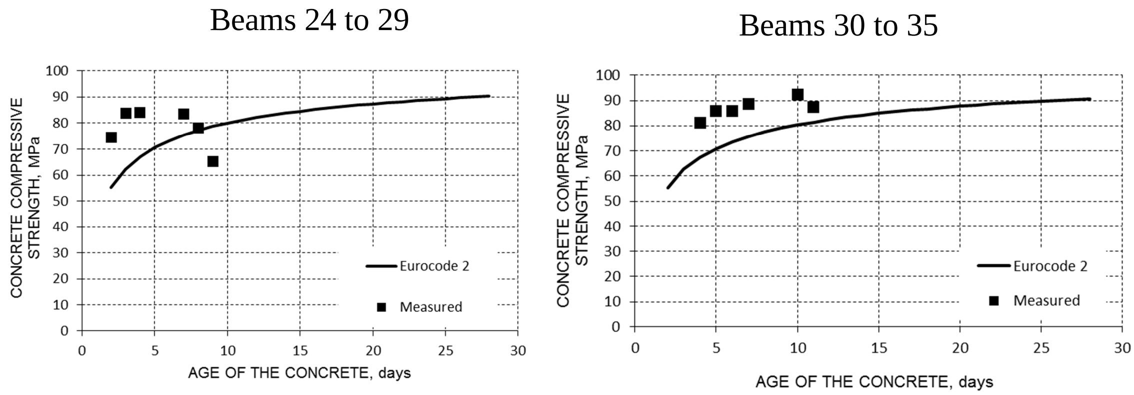


Figure. 14 Measured and calculated compressive strengths at early age

For beam 29 e.g. the average compressive strength is 65.3 MPa, which is the lowest value in its series. The highest average value here is 84.1 MPa and occurred for beam 28. However, this remarkable difference of 18.8 MPa is not reflected in the graphs in Figure 10. A similar observation is valid for beams 30 to 35 where the difference of 11.2 MPa between the lowest and highest measured compressive strength at the time of release is not reflected in the measured strain in the transfer zone.
In addition, the considered beams' compressive strength at early age is generally higher than estimated based on the measured strength at 28 days. This hinders the use of this important parameter in the assessment of the transfer length.

➢ *The way of the release and the strand diameter*

Only for beams 3 to 6 the strands are released in a sudden way. Therefore, a clear conclusion regarding the way of release cannot be made. The same can be concluded regarding the strand diameter because nearly all strands are seven wire strands of ½". This will be a subject for further research.

CONCLUSIONS

The study starts with an FEM of the end zone of a pretensioned girder. The preliminary conclusion is that the transfer length has a major influence on the stresses in the concrete and in the reinforcement. For that reason, a parametric study is conducted, in which different formulations for calculating the transfer length, found in literature, are compared. The study demonstrates that the concrete strength class, the time of release, the strand diameter, and the way of prestressing may be determining factors for the transfer length, but in general a large scatter of the results is observed. Based on this, no unanimous conclusion can be found on how to calculate the transfer length as an input for finite element analysis of an end zone. Therefore, experimental research was carried out on several girders produced in a prefab concrete plant. The results of the strain measurements render a clear influence of the concrete strength, a possible influence of the location of the measurement points, and a certain influence of the concrete strength at early age which is difficult to quantify. The way of releasing the strands seems to have no effect on the transfer length. Further research will consist of extra measurements at different levels at the lateral faces of the beams. From these data and the knowledge of the concrete strength at the time of release, the FEM will be optimized. Such an analysis of the transfer length provides a good reference frame for further research of the end zone of a prestressed girder.

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